**Unbalanced Current Sharing Control in Islanded Low Voltage Microgrids**

**Supplementary material: stability and sensitivity tests**

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# Introduction

To test the system stability when faults happen and to test the applicability of reported control method with different system parameters, we designed four experiments. The goal for the first three is to test what will happen to the system when line impedance and inductance changes while different types of faults occur in the system. A robust controller should be able to operate the system and keep the voltage and frequency within the acceptable range regardless of the configuration of the network and the disturbances that may happen in the system.

The network has three loads (two local loads and one shared load) and two DG units, as shown in Figure 1. The tests are evaluated on three configurations of distribution lines. Note that in each case, we refer to line 1 as the "shorter" distribution lines and line 2 as the "longer" distribution lines. The value of line 3 doesn't change through the test and only the value of line 1 and 2 changes.

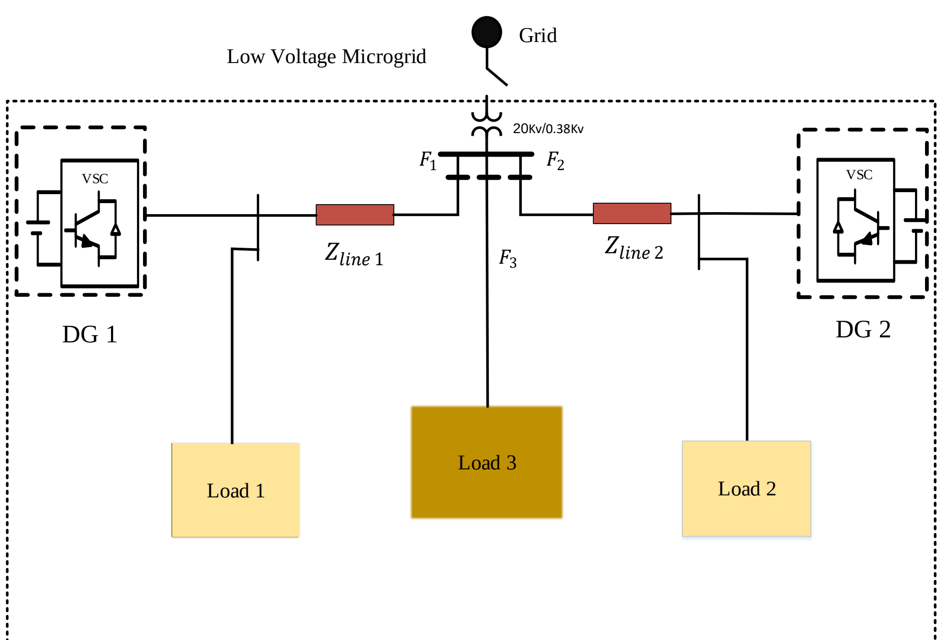


*Figure 1. Schematic diagram of low-voltage microgrid*

The first test measures the abilities of a network when the distribution lines are shorter, e.g., 100 and 200 meters for the shorter and longer distribution lines, respectively. The second experiment tests the ability of the network when the microgrid is larger. Therefore, arbitrarily, we test the network when the distribution lines are 300 and 600 meters for shorter and longer distribution lines.

To show that the control system does not only work for a specific distribution line resistance/reactance ratio, we tested a highly asymmetrical microgrid where one of the distribution lines are much longer than the other line. In other words, one DG unit is isolated from the rest of the network. In this case, voltage control will be more challenging. Also, when a fault happens, its impact is more local since DG units are isolated. This will be a challenging issue for microgrids to control and operate a system under disturbances. The distribution lines for the third test are 100 and 600 meters for shorter and longer distribution lines respectively.

In all tests, we measure the ability of the control system to share currents and also apply three faults per test. This is to test a variety of possible fault scenarios that could happen to the system. The system should be able to manage these disturbances no matter where faults are and what type of fault happens in each location.

For simplicity, the loads in the system are the same for all tests. In each test, first, one fault happens after a short time (0.2–0.45 seconds) and persists until the relay disconnects the faulted line from the system. About 0.1 seconds after the relay trips, the fault is cancelled and the line is reconnected to the network. Half a second after the first fault, a second fault occurs, and then a third fault occurs half a second after that.

Although this is not a physically realistic sequence of events for a distribution network, it allows rapid testing of the performance of the controller before, during and after fault occurrences. The variations in network topology between and during tests also test the ability of the controller to work under a variety of network configurations without any adjustments to its parameters (i.e., sensitivity testing).

In all tests, first a line to ground (L-G) fault happens, second, a line to line fault (L-L) followed by a (L-L-L) fault. Therefore, in each test, the distribution line configuration and position of faults changes. The timing of the fault occurrence is the same for three tests. Table 1 shows the location of occurrence of each fault, the type of each fault at each location and the corresponding line impedance of the micro-grid. Table 2 shows the timing of fault occurrence, fault clearance, and reconnection of the load to the network.

*Table 1. Network configuration and fault location for all test cases*

| **Network configuration** | **Short Line Impedance** | **Long Line Impedance** | **Fault 1 Location (L–G)** | **Fault 2 Location (L–L)** | **Fault 3 Location (L–L–L)** |
|---|---|---|---|---|---|
| Short line | R=0.01, X=0.001 | R=0.02, X=0.002 | L1 | L2 | L3 |
| Longer line | R=0.03, X=0.003 | R=0.06, X=0.006 | L2 | L3 | L1 |
| Long line and higher resistance | R=0.01, X=0.001 | R=0.06, X=0.006 | L3 | L1 | L2 |
| Generator trip | R=0.01, X=0.001 | R=0.02, X=0.002 | DG1 trip | DG2 trip | — |

*Table 2. Timing of fault occurrence, clearance and reconnection of load*

| | **Fault 1 (L–G)** | **Fault 2 (L–L)** | **Fault 3 (L–L–L)** |
|---|---|---|---|
| Fault Occurrence (s) | 0.20 | 0.70 | 1.20 |
| Faults Clearance (s) | 0.32 | 0.80 | 1.32 |
| Load Reconnection (s) | 0.45 | 0.95 | 1.45 |

In addition to the line fault tests described above, we conduct one additional series of tests, in which each of the DG units is tripped offline in turn: first DG1 is tripped offline after 0.15 s, then it is restored at the 0.3 s mark, then at the 0.6 s mark DG2 is tripped off for 0.2 s.

Results from each of these tests are given in the sections that follow.

# 1. Short Line Fault Test

The impedances of the lines are shown in Table 1. Figure 2 shows the current components of feeders throughout the test. The single-phase fault is triggered at the terminal of DG1 (local load 1). When the faults start, the unbalanced current of feeder one spikes up. It also causes the current on other feeders to drop somewhat, since the high current drawn by local load 1 causes a voltage drop which consequently, decreases current drawn by other loads. The second fault (L-L) happens at the shared load. The magnitude of the shared load fault is smaller than the local load fault since the impedance from the shared load to the DG units is more than the local loads due to the distribution lines. The third fault (L-L-L) is a balanced fault. Therefore, it doesn't have negative and zero sequences current except for a short transient time.

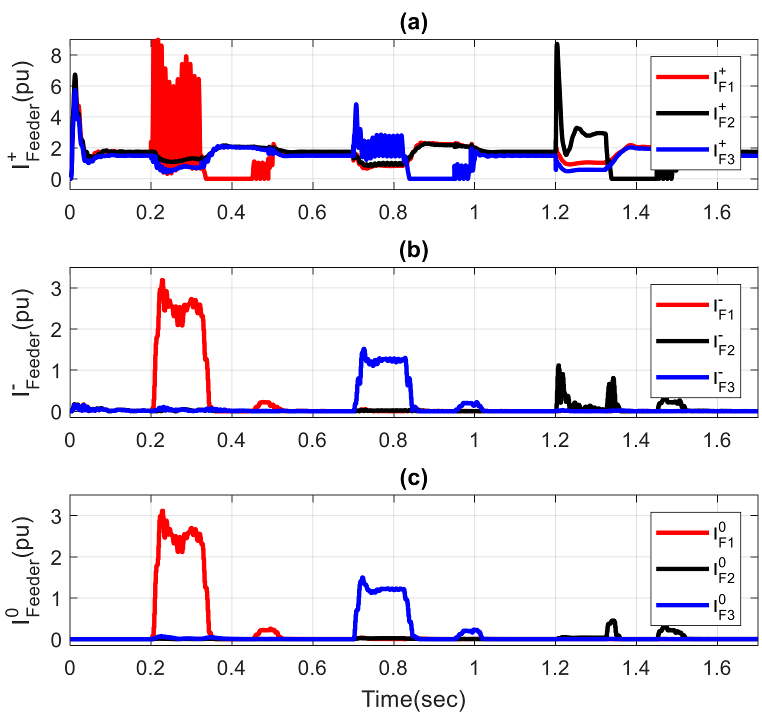


*Figure 2. Positive- (a), negative- (b) and zero-sequence (c) current components during short line tests*

Figure 3 shows the active and reactive power consumed by each feeder during the test. When the fault happens, a double frequency ripple shows up on each feeder except for the L-L-L fault since it is balanced. When each fault clears, its power consumption goes to zero and returns to normal mode when the load connects back after the faults. All the loads are the same and consume the same amount of power. However, the shared load consumes a bit less than the other two loads since the voltage at shared load feeder is a bit less than the voltage at DG terminals due to distribution line voltage drop.

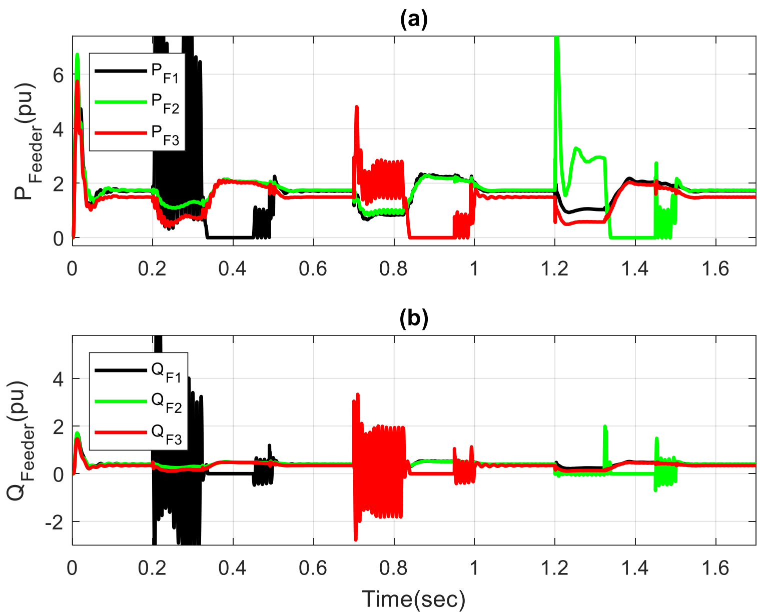


*Figure 3. Real (a) and reactive (b) power on all three system feeders during short line tests*

Figure 4 shows the output current of both DG units through the test. When the first fault (L-G) happens, the output current of DG1 on one phase spikes up. However, the output current on DG2 terminal increases a bit since the location of the fault is much closer to DG1. The same happens when the L-L-L fault happens. It causes the output current of DG2 to go up around four times higher than the normal mode. The L-L fault has an almost equal effect on both loads since it is between them. However, since the distribution line between the shared load and DG1 is shorter, DG1 provides more current than DG2 during this period. In the times when there is no fault, the current is shared well, and both units provide almost the same amount of current.

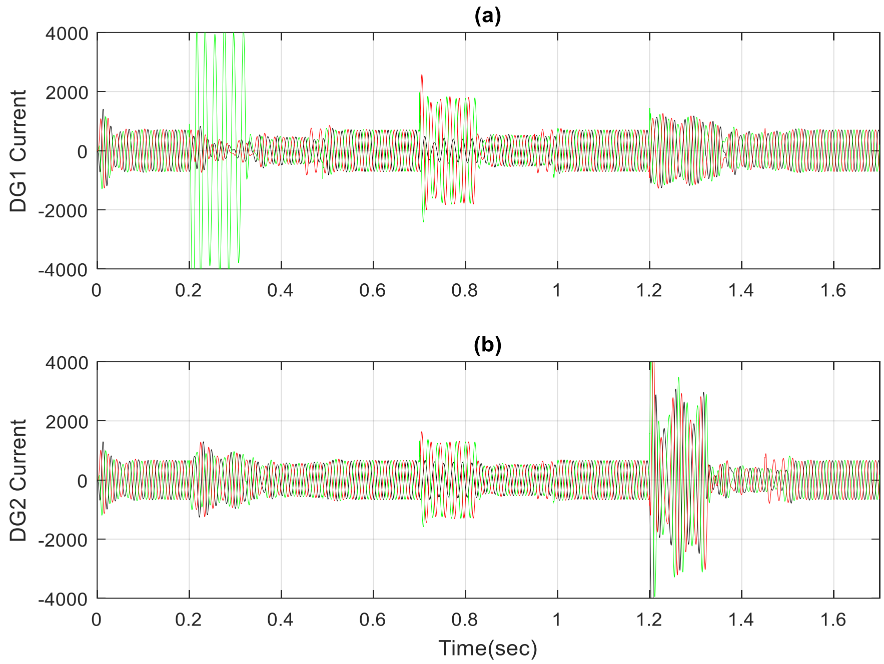


*Figure 4. Current from both DG units during short line tests*

Figure 5 shows the droop performance during the test. During the faults, a double frequency disturbance appears in both frequency and voltage. Due to the difference in line impedances, the output voltage of the units is somewhat different, but the frequency is the same in all parts of the microgrid. Every time that faults happen, the voltage and frequency drop due to increased power consumption. The V-P and F-Q droop shows that can manage the microgrid properly and returns the system to normal state every time the fault is cleared in a short transient. When the relay disconnects the load, the frequency and voltage rise somewhat since the total load in the systems is decreased. Since the loads consume about four times more active power than reactive power, the changes in voltage due to VP droop is more visible than the changes in frequency caused by FQ droop. When the L-G fault at DG1 terminal happens, the output voltage for DG1 decreases more than DG2 terminal since unit 1 provides more of the extra energy consumed when the fault happens. The same happens when the L-L-L fault happens at t=1.2s. In this time the voltage output of DG2 decreases more than DG1 since in this experiment the L-L-L happens at the terminal of DG2.

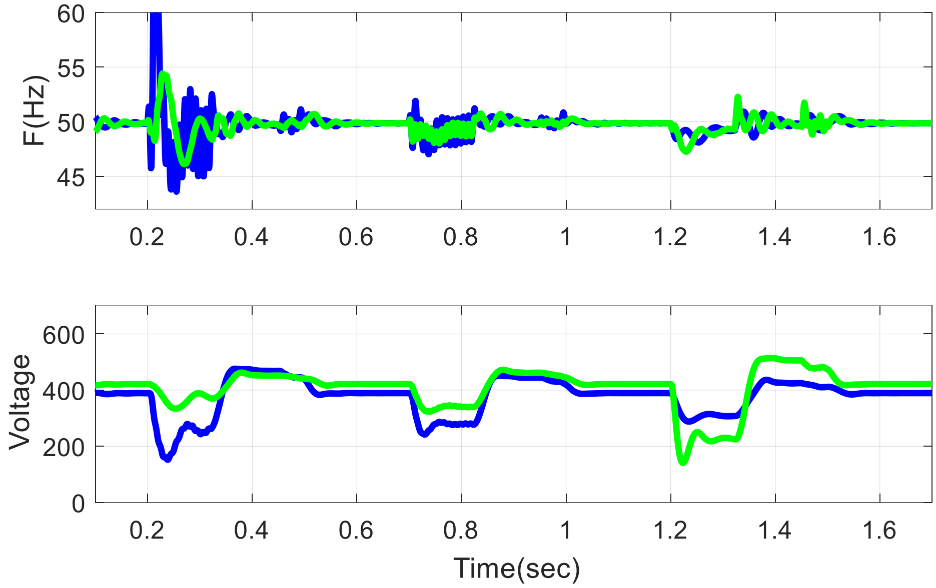


*Figure 5. System frequency and voltage at two DG buses during short line tests*

Figure 6 shows the active and reactive output power of DG units. When the unbalanced faults happen (L-G and L-L), a double frequency ripple shows up on DG unit active and reactive power. The magnitude of ripple corresponds to the amount of unbalanced power each unit provides during the fault. Since the L-L-L fault is balanced, it does not cause any double-frequency ripple on the output of units at t=1.2s.

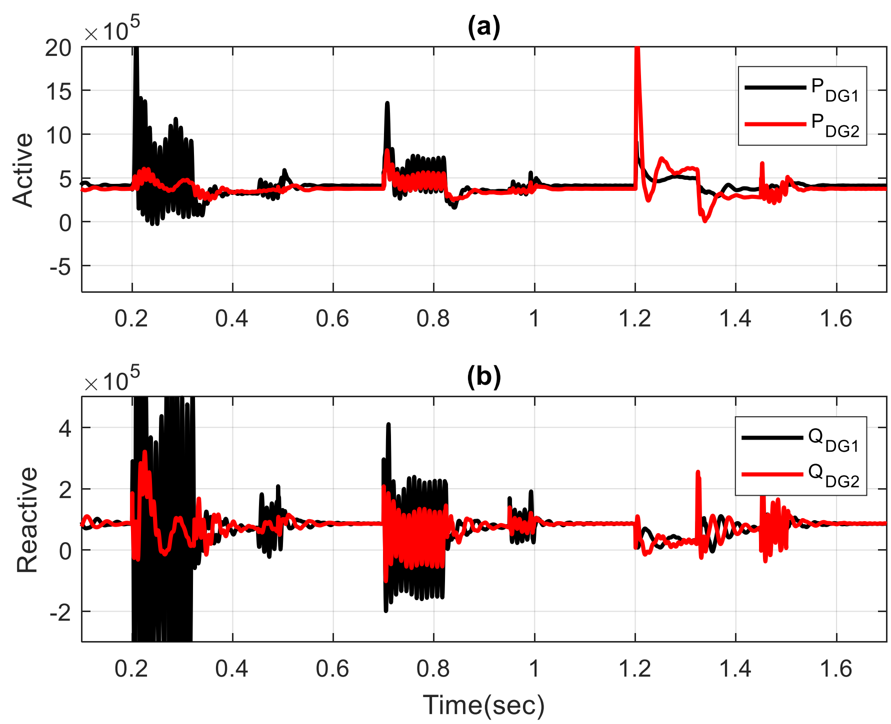


*Figure 6. Active (a) and reactive (b) power from two DG units during short line tests*

## 2. Long Distribution Line Microgrid

This experiment tests the performance of the control system when the microgrid distribution line becomes longer, as well as its ability to recover from extreme fault conditions and also the ability to return back to a normal state. In this test, the length of each distribution line triples (the length ratio of DG2 to DG1 distribution line remains 2). Also, to show that the control system can manage any kind of fault in any position, the location of faults changes according to Table 1.

Figure 7 shows the current component of feeders. The L-G fault which happens at t=0.2s is located at the shared load. This time the fault sees higher resistance since it is not located at the local load. Furthermore, due to an increase of line impedances, the shared loads see even more resistance and inductance. Also, we see a spike at feeder 1 and 2 where the L-L-L and L-L faults happen.

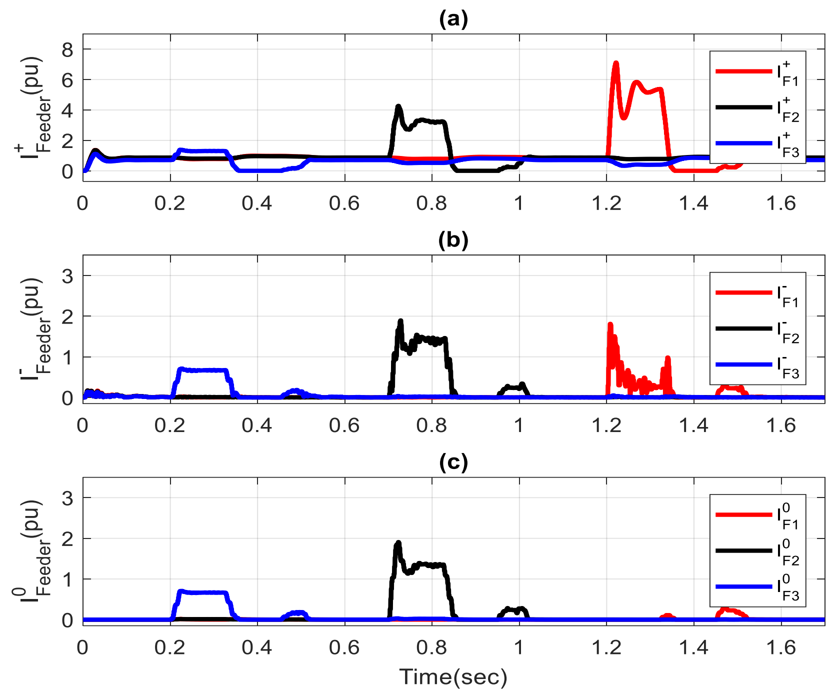


*Figure 7. Positive- (a), negative- (b) and zero-sequence (c) current components during long line tests*

Figure 8 shows the active and reactive power flow on the feeders during this test. The power consumption of the shared load is even less than the previous experiment when the distribution lines were shorter.

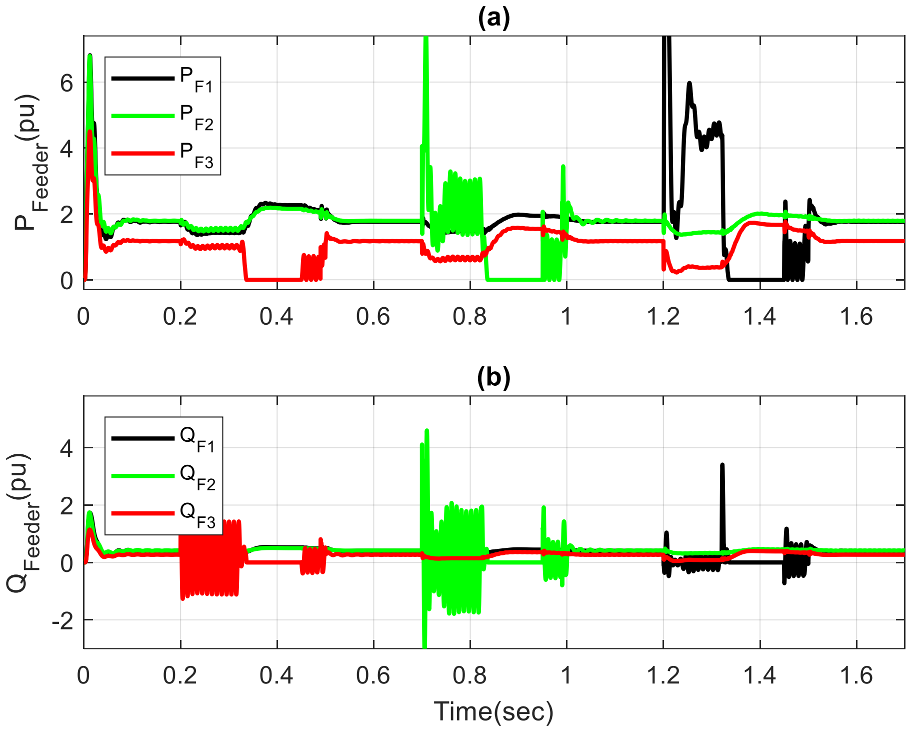


*Figure 8. Real (a) and reactive (b) power on all three system feeders during long line tests*

Figure 9 shows the real-time current of DG units. It shows that when the distribution lines become longer, the impact of fault the becomes more local and draws more current from the adjacent DG unit.

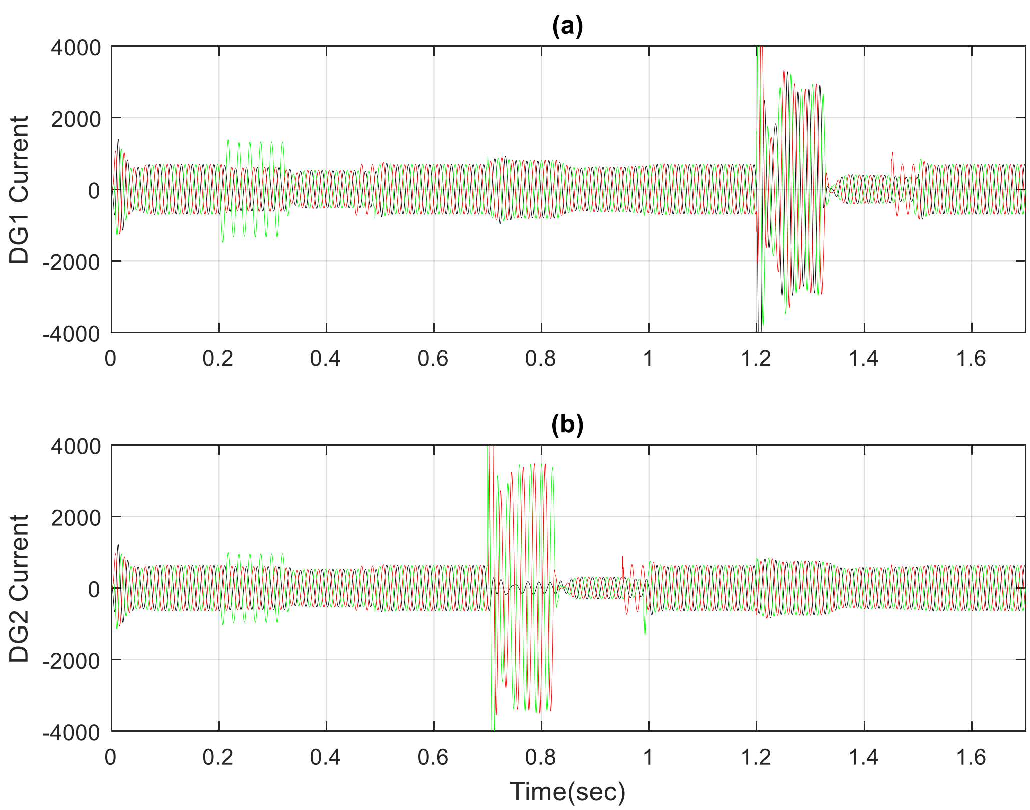

*Figure 9. Current from both DG units during long line tests*

Figure 10 shows the frequency and voltage of the DG units. When the extreme fault happens at DG terminals at t=0.7 and t=1.2 for DG2 and DG1 respectively, the voltage drops drastically for the adjacent unit. However, when the fault clears, the unit adjacent to the fault starts to recover and raises voltage even higher than normal mode since when the fault is cleared, the units see less load in the system and increase their voltage output level. However, the unit adjacent to the fault increases its output even more since less power is being drawn from it in the transient time. The system is quite stable throughout the test even though there is a highly unbalanced fault in the system. This is mainly due to the robust design of the voltage and current controller which is discussed in the main body of the paper. The controller has a very high gain at the desired frequencies (this controller can also manage harmonic load since it is designed in a way that not only has high gain in main frequency, i.e., 50 Hz, but also high gain at 150, 250, 350, up to 13$^{th}$ harmonic. However, since the focus of this work is on imbalance sharing, we don't cover the harmonic compensation abilities of the proposed control system). Also, it has infinite gain margin and 30 degrees gain margin which is a robust design and helps balance the system when disturbance (i.e., faults and unbalance) is introduced to the system.

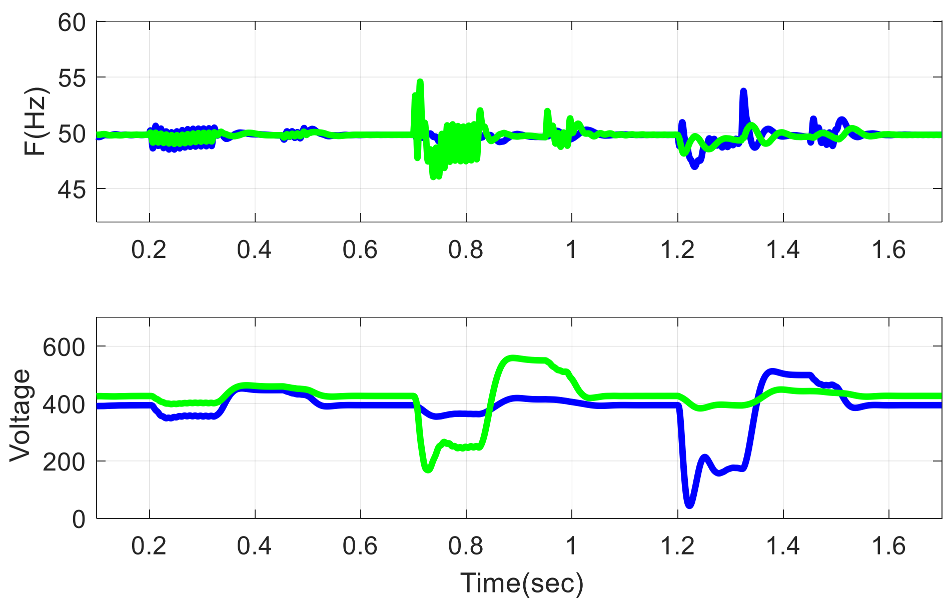


*Figure 10. System frequency and voltage at two DG buses during long line tests*

Figure 11 shows the active and reactive power output of DG units. During the fault times, we see a double frequency on power component of units where the share of each unit of the unbalanced power corresponds to the magnitude of double frequency ripple on its output.

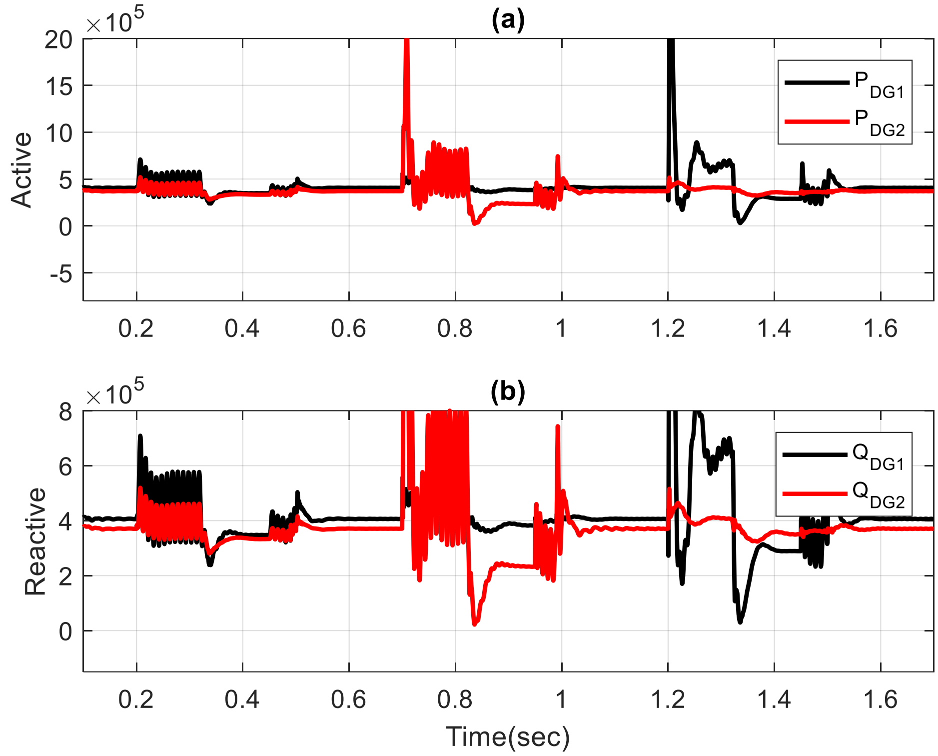


*Figure 11. Active (a) and reactive (b) power from two DG units during long line tests*

## 3. Highly Asymmetrical Microgrid

This experiment tests the microgrid when it is highly asymmetrical, i.e., one of the distribution lines is much longer than the other one (6 times more). This will be challenging for a small microgrid to share power components and keep voltage and frequency stable. This test is designed to examine whether a highly asymmetrical microgrid can operate and can endure faults at different locations. A stable network should be able to keep its voltage and frequency within an acceptable range and should be able to recover from severe disturbances.

Figure 12 shows the current component of feeders for this experiment. When a fault happens at a local load of DG2, most of current is drawn from DG2, since the distribution line between DG2 and the rest of the microgrid is very long.

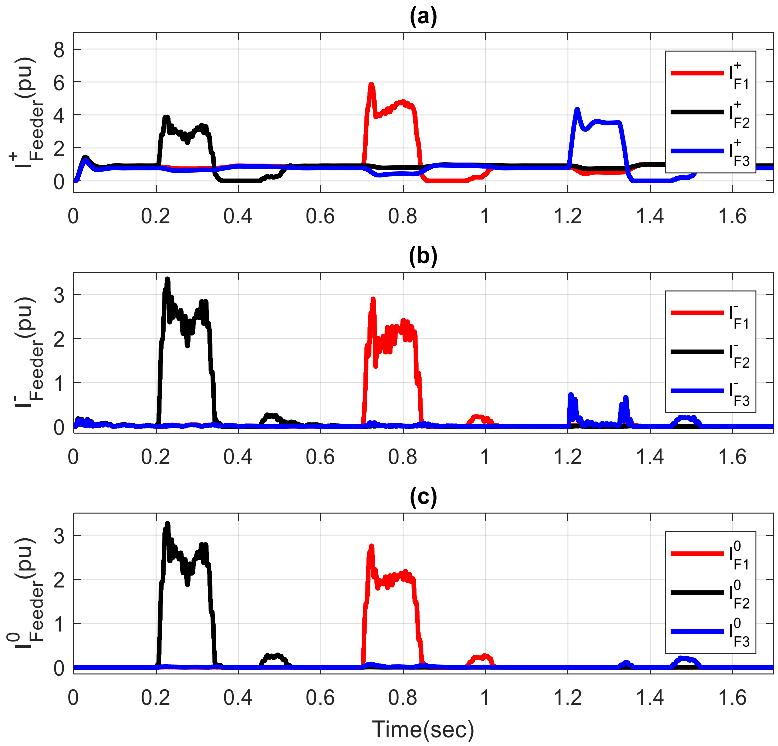


*Figure 12. Positive- (a), negative- (b) and zero-sequence (c) current components during asymmetrical microgrid tests*

Figure 13 shows real and reactive power transfers across the feeders. Due to the large impedance of distribution line 2, the voltage at feeder 3 (shared load) is lower than the terminal voltage of DG2. Also, the output voltage of the DG1 terminal is closer to the shared load feeder since it has a shorter line in comparison to DG2. This causes that the voltage at the DG2 terminal is higher. Therefore, the local load at DG2 terminal consumes more power.

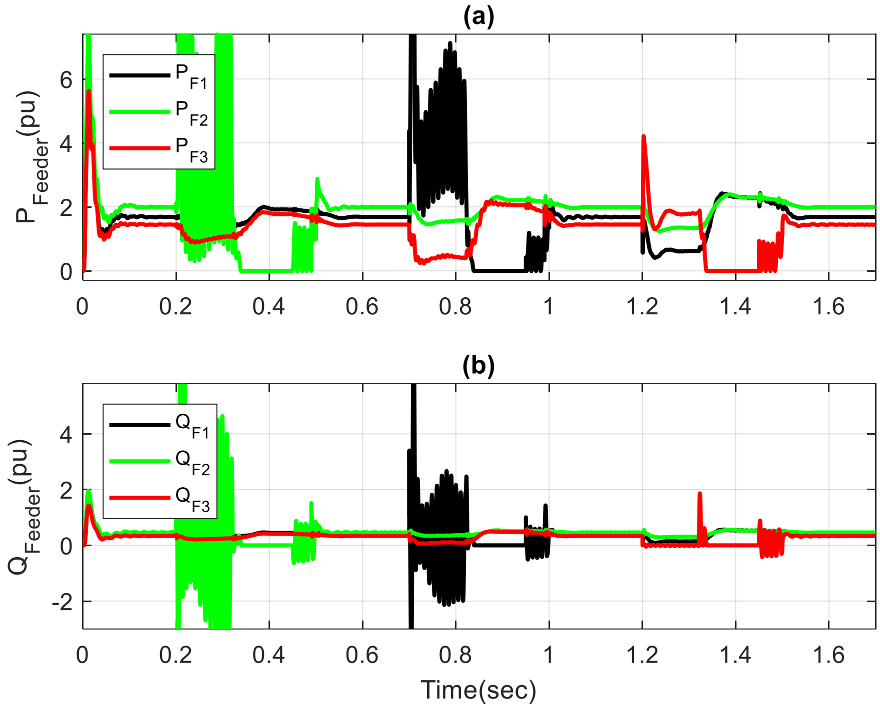


*Figure 13. Real (a) and reactive (b) power on all three system feeders during asymmetrical microgrid tests*

Figure 14 shows the voltage and frequency of DG units. As discussed before, the voltage at the DG2 terminal is slightly higher than DG1 due to the longer distribution line. When the fault happens, the voltage at DG2 drops drastically. When the fault clears, DG2 voltage goes higher than normal since it has no local load to share and also it has far distance from the rest of the microgrid. When the L-L fault happens at DG1 terminal at t=0.7s, the voltage output of DG1 decreases and the DG2 voltage also decreases to a lesser degree. When the L-L-L fault happens, the voltage at the DG1 terminal drops more than DG1 voltage output since DG1 is closer to the fault locations. All these operations are performed by the droop system autonomously. The frequency also is the same for both units. This experiment shows the excellent performance of the droop system. Not only can it handle the voltage and frequency properly; it also can recover the system to normal mode without any instability and within a very short transient time.

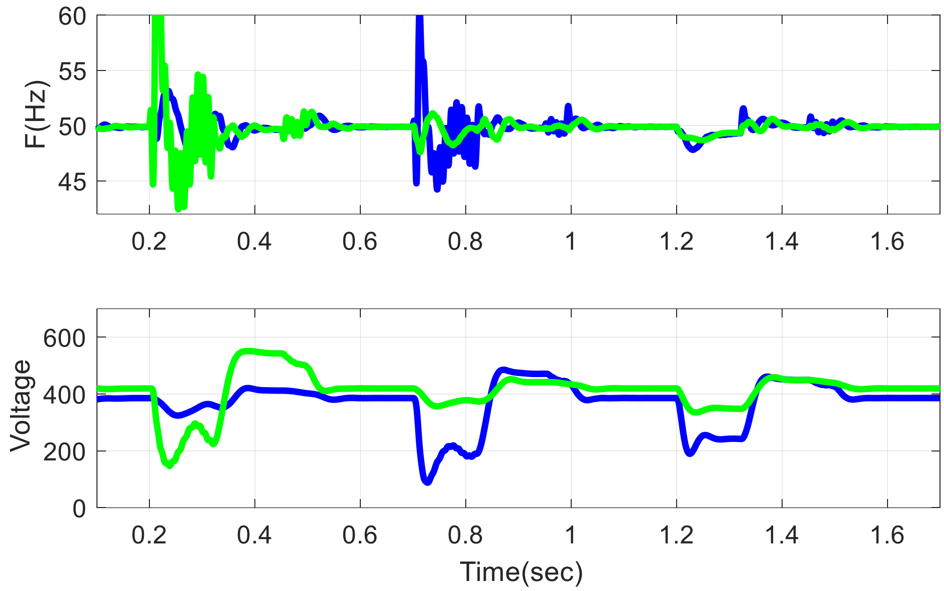


*Figure 14. System frequency and voltage at two DG buses during asymmetrical microgrid tests*

Figure 15 shows the output current of both DG units. Since DG1 is closer to the shared load, it provides a larger share of the current to the fault that happens at t=1.2s at the shared load location.

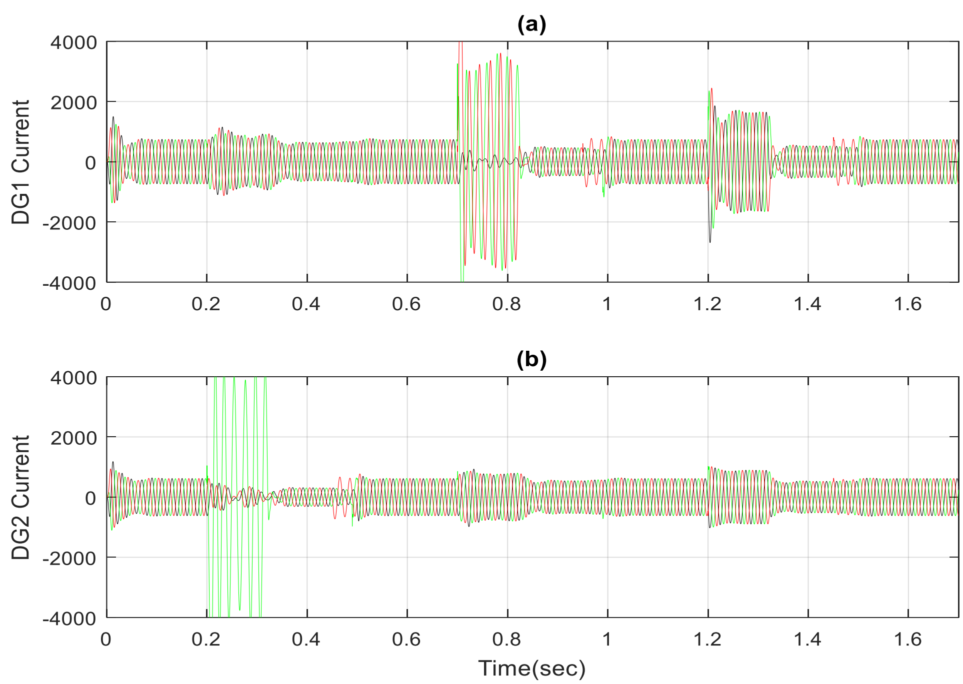


*Figure 15. Current from both DG units during asymmetrical microgrid tests*

Finally, Figure 16 shows the active and reactive output power of the DG units. Despite the large difference between distribution lines, the VP & FQ droop can perform power sharing between units perfectly. The reactive power sharing is 100 percent accurate and active power sharing is almost accurate.

These experiments show that control system is extremely robust and can share power components accurately regardless of the configuration of the microgrid (insensitive to changes in system parameters) and is extremely stable regardless of what kind of fault happens at what location in the microgrid. It handles all the tested situations properly and continues to work autonomously when disturbances are resolved.

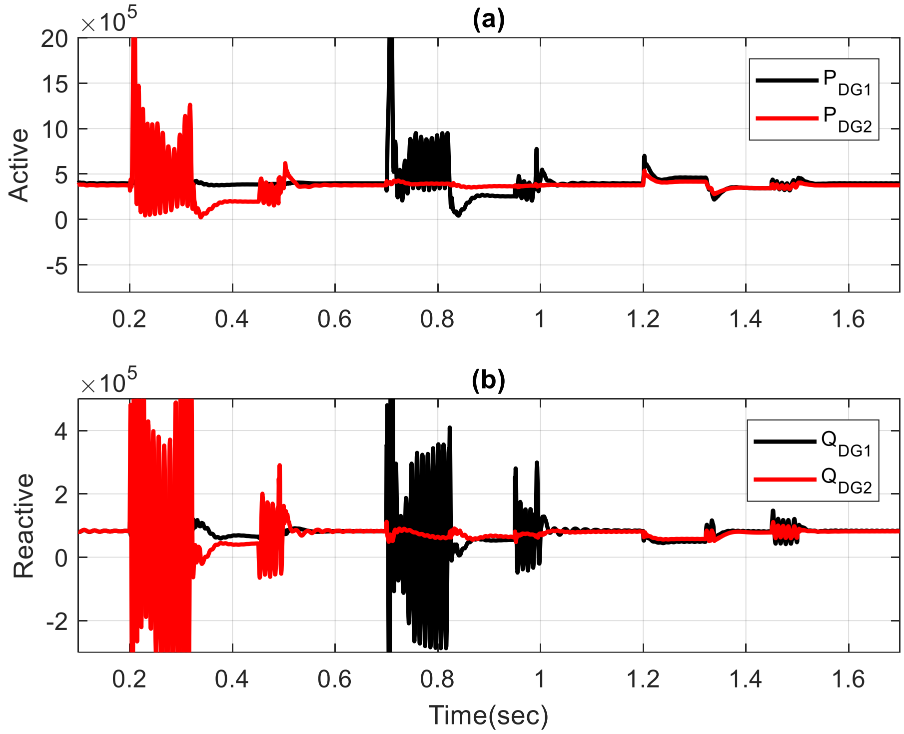


*Figure 16. Active (a) and reactive (b) power from two DG units during asymmetrical microgrid tests*

# 4. Generator Trip

This test is designed to evaluate the ability of the control system when for any reason a DG unit trips. In this test first DG1 trips at t=0.15s and disconnects from the network. After about 0.15 second, it is reconnected back to the power system. The same scenario happens to DG2 starting at t=0.6s.

Figure 17 shows the active and reactive power flow on the feeders. When DG1 trips at t=0.15s, the power consumption of local load 1 and shared load drops to a large extend. The power of local load 1 even drops more since it is at the end of the line for DG2. The same happens when DG2 trips. However, since all loads must be fed by only one unit, the voltage reference of the active unit drops more. Furthermore, the voltage at the opposite side of the active DG is lower. Because of this, the total load fed by one unit is lower than when both units are active.

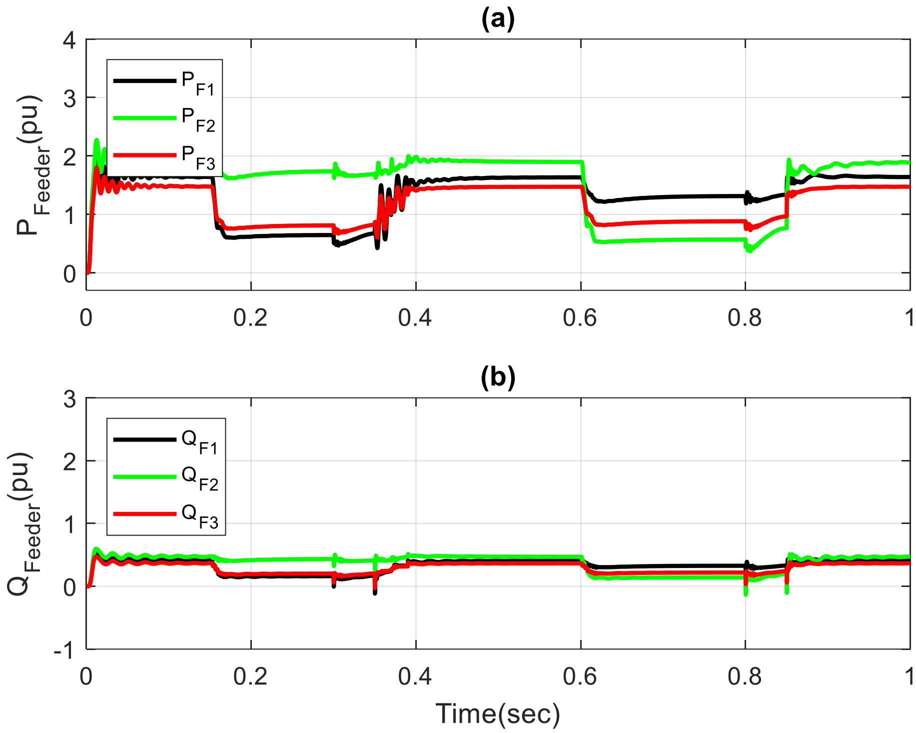


*Figure 17. Real (a) and reactive (b) power on all three system feeders during generator trip tests*

Figure 18 shows the output current of the DG units during the generator trip tests. When a DG trips, its output current reaches zero and the output current of the active DG increases.

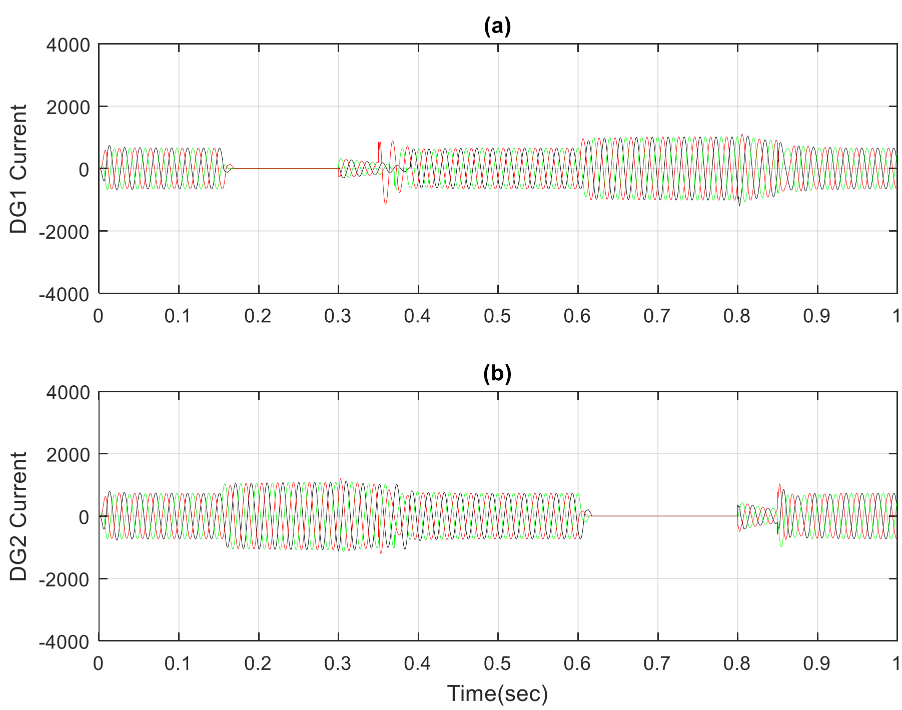


*Figure 18. Current from both DG units during generator trip tests*

Figure 19 shows the frequency and voltage output of the DG units. When a fault happens, the voltage and frequency of the disconnected unit start to rise since it sees no load. at the same time, the connected unit decreases its voltage and frequency since it is feeding all the loads in the system. Throughout the test, voltage and frequency are within acceptable ranges. Also, the DG units are able to recover voltage and frequency in a short transient time.

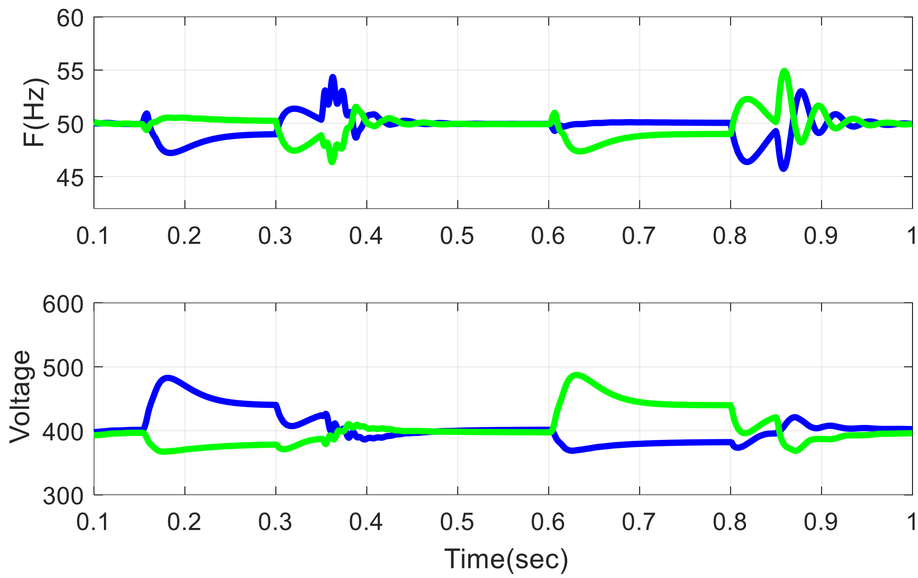


*Figure 19. System frequency and voltage at two DG buses during generator trip tests*

Figure 20 shows the active and reactive power output voltage of the DG units. When a DG disconnects, its power output reaches zero and the other unit increases its production. However, the increase in power production will not be double the time when units works together due to the aforementioned voltage drop at microgrid terminals.

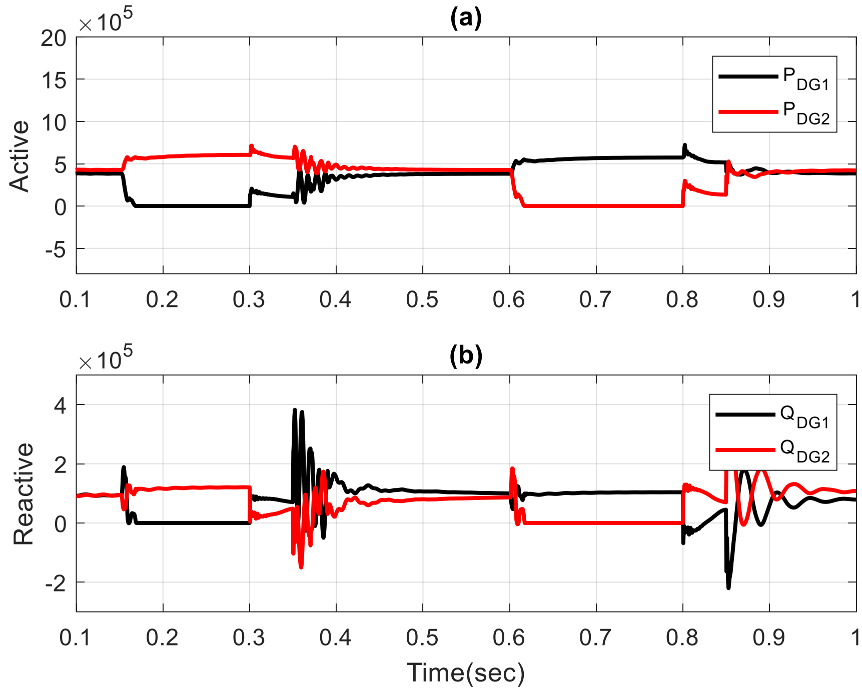


*Figure 20. Active (a) and reactive (b) power from two DG units during generator trip tests*

Overall, the system is very robust and is able endure extreme conditions and recover to normal state in a short amount of time. This is due to the effective design of the droop control, voltage and current system. The control system is robust and can operate correctly under normal and fault conditions with a wide variety of microgrid structures.